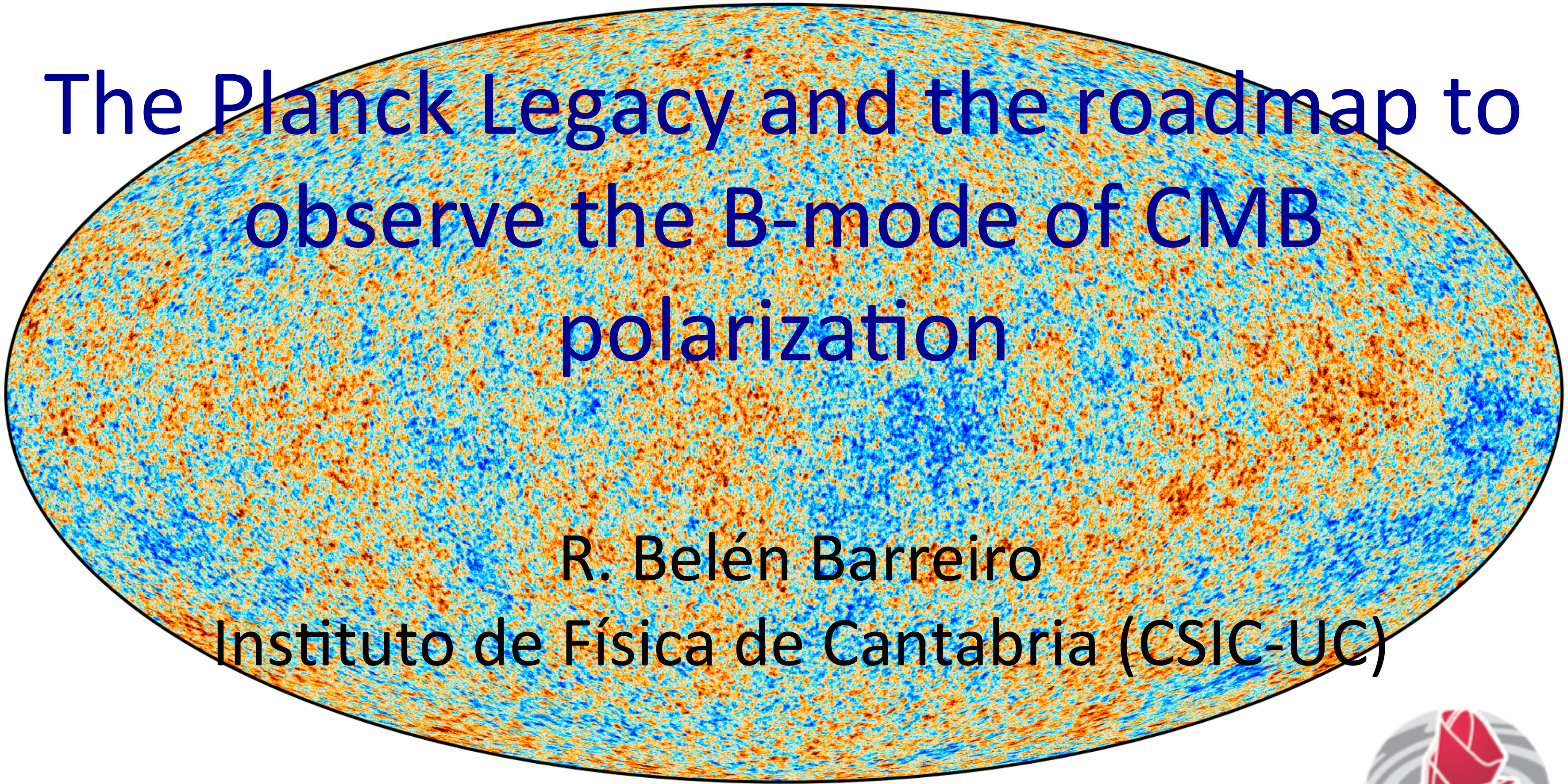

The Planck Legacy and the roadmap to observe the B-mode of CMB polarization

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Instituto de Física de Cantabria (CSIC-UC)

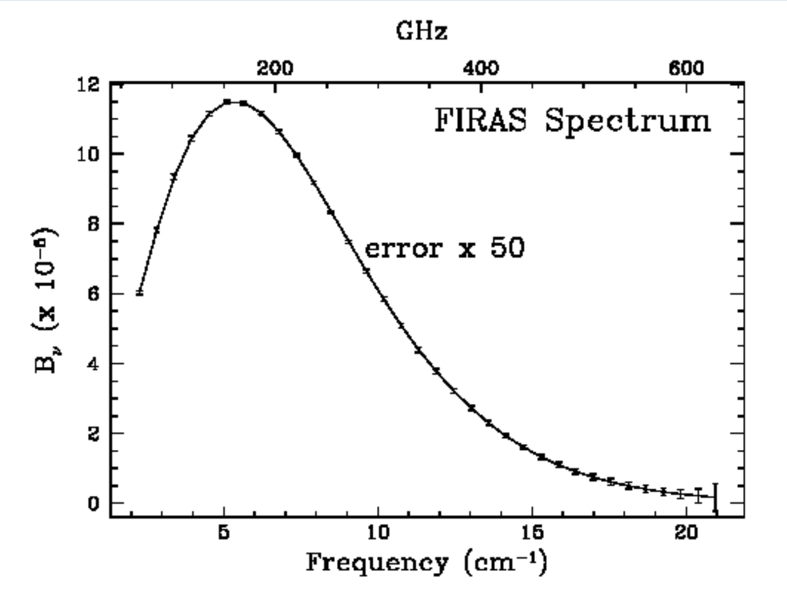
VII Meeting on Fundamental Cosmology, Madrid, 9th-11th September 2019

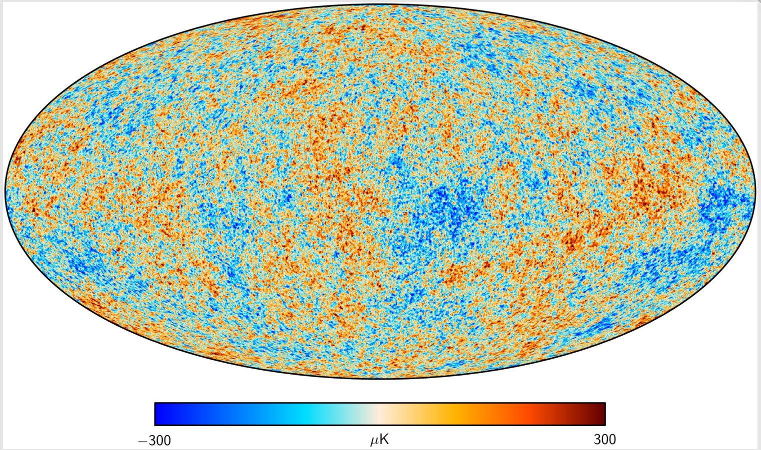
Outline

- Introduction
- The Planck Mission: highlights of results
- The quest for the B-mode of polarization

The Cosmic Microwave Background (CMB)

The **CMB** is a **homogenous and isotropic radiation** that has travelled to us from the last scattering surface since the universe **was 380,000 years-old**, with very little changes or interactions (besides its cooling or redshift due to the expansion of the universe). It has a blackbody spectrum with T_0=2.725K





The CMB presents small anisotropies at the level of ~10^{-5}, which encode a wealth of information about the early Universe, its content and evolution.

The polarization of the CMB provides a unique probe of inflation.

Its interaction with the Large Scale Structure of the Universe in its way to us also provides additional information.

The key observable: the angular power spectrum

- The CMB fluctuations are described as a random field on the sphere. It is usually written as a expansion on spherical harmonics

$$\frac{\Delta T}{T_0}(\vec{n}) = \frac{T - T_0}{T_0}(\vec{n}) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vec{n}) \ , \qquad \ell \sim 180^0 / \theta$$

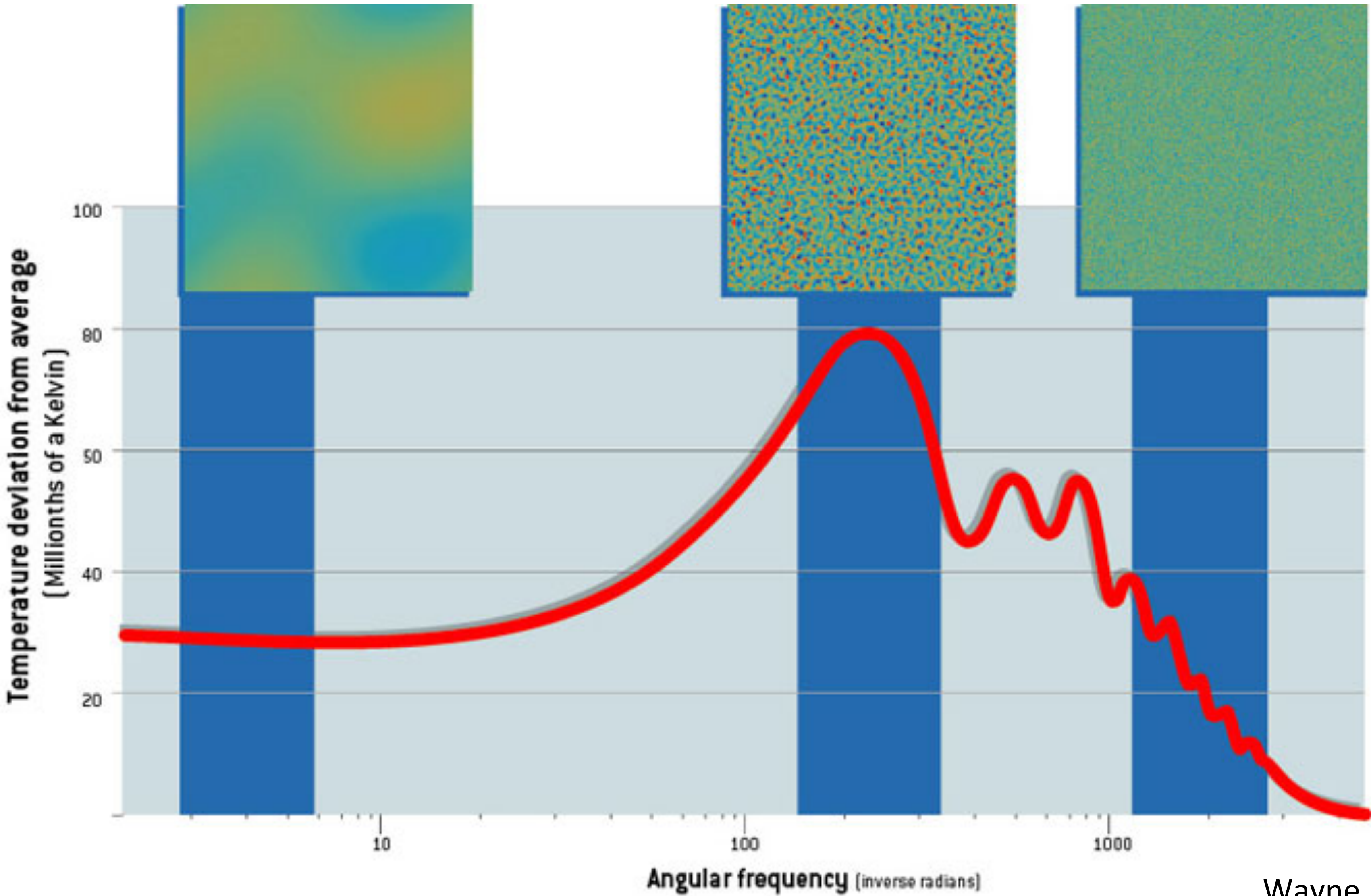
$\vec{n}$ is a unit vector on the sphere

- The $a_{\ell m}$ are complex random variables of zero mean that, assuming isotropy of the fluctuations, satisfy

$$\left\langle a_{\ell m} a^*_{\ell' m'} \right\rangle = C_\ell \delta_{\ell\ell'} \delta_{mm'}$$

- The C_ℓ's constitue the angular power spectrum, which depends on the cosmological model
- If the field is Gaussian, all the statistical information is contained on the C_ℓ's

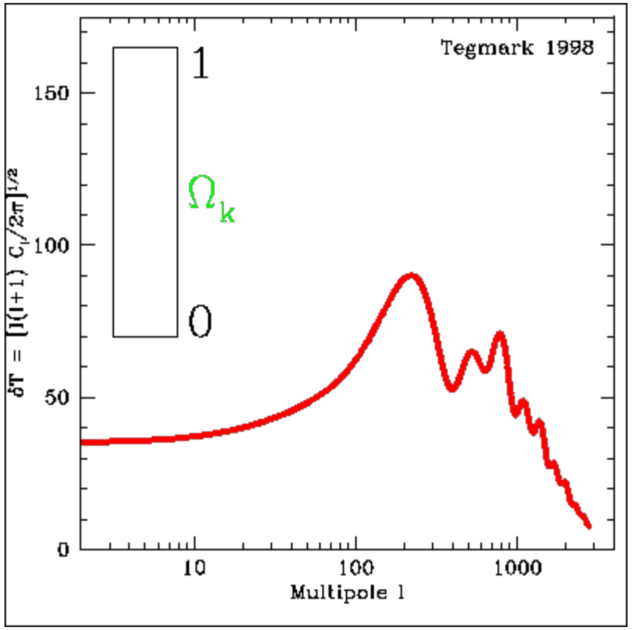
CMB temperature power spectrum



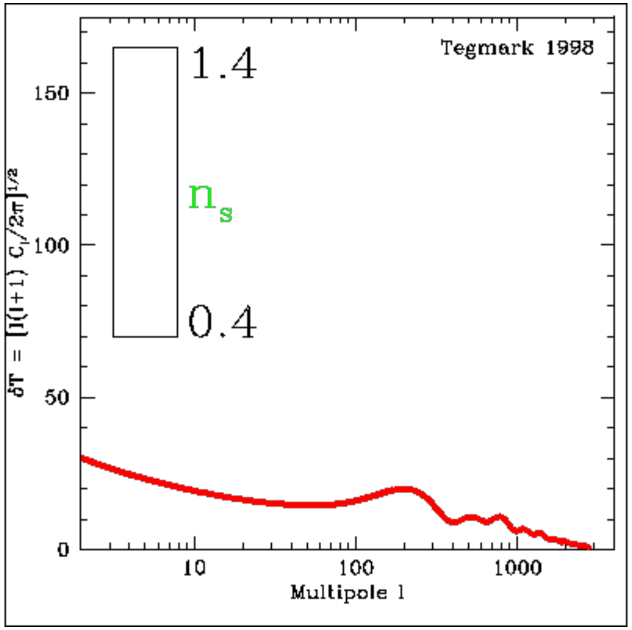
Wayne Hu

Dependence of CMB power spectrum on cosmological parameters

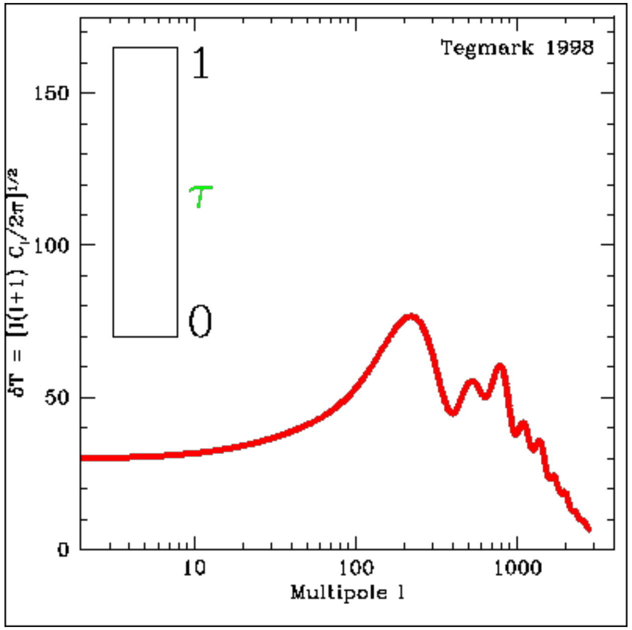
Curvature



Spectral index



Reinoization

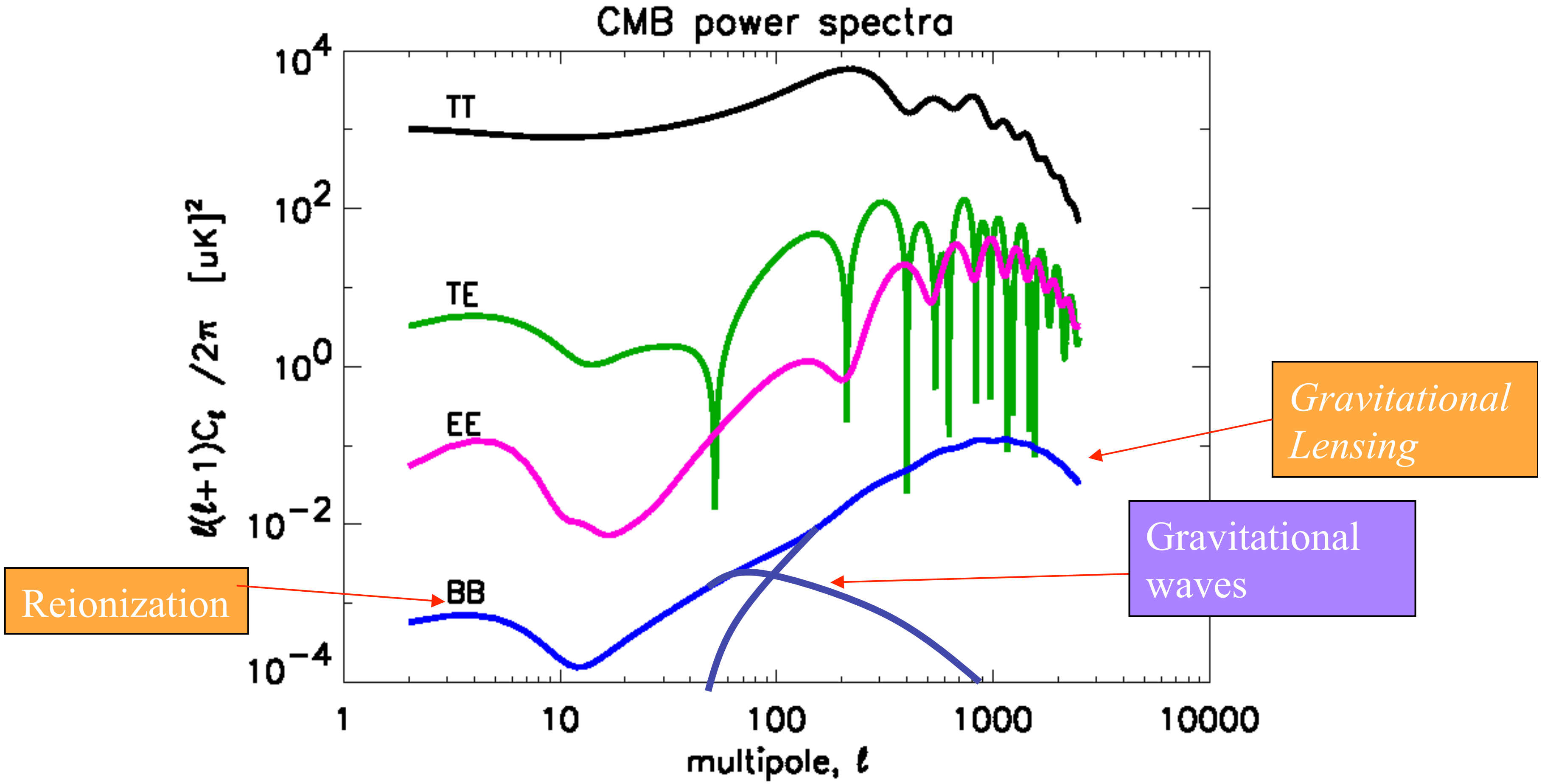


- Different cosmological parameters affect in different ways to the shape of the CMB power spectrum
- By fitting the observed C_ℓ´s to theoretical predictions, the cosmological parameters can be estimated

CMB polarization

- CMB is partially and linearly polarised (polarization produced by Thomson scattering in the Last Scattering Surface)
- Linear **polarisation is defined locally**, in terms of the so-called **Stokes parameters Q and U**
- Full-sky polarization maps can be decomposed into two components, the E-modes and the B-modes, (invariant under rotation) and are related to the Q and U Stokes parameters by a non-local transformation
- We can also generate auto- and cross-angular spectra for polarization, so we have: TT, EE, BB and TE (EB and TB are expected to be zero)
- Scalar perturbations produce only E-mode of polarization
- Primordial gravitational waves (predicted by inflation) produce both E and B-mode polarization → **if we detect primordial B polarization, we have (indirect) proof of primordial gravitational waves !!**
- Reionization and CMB lensing can also introduce B-mode polarization

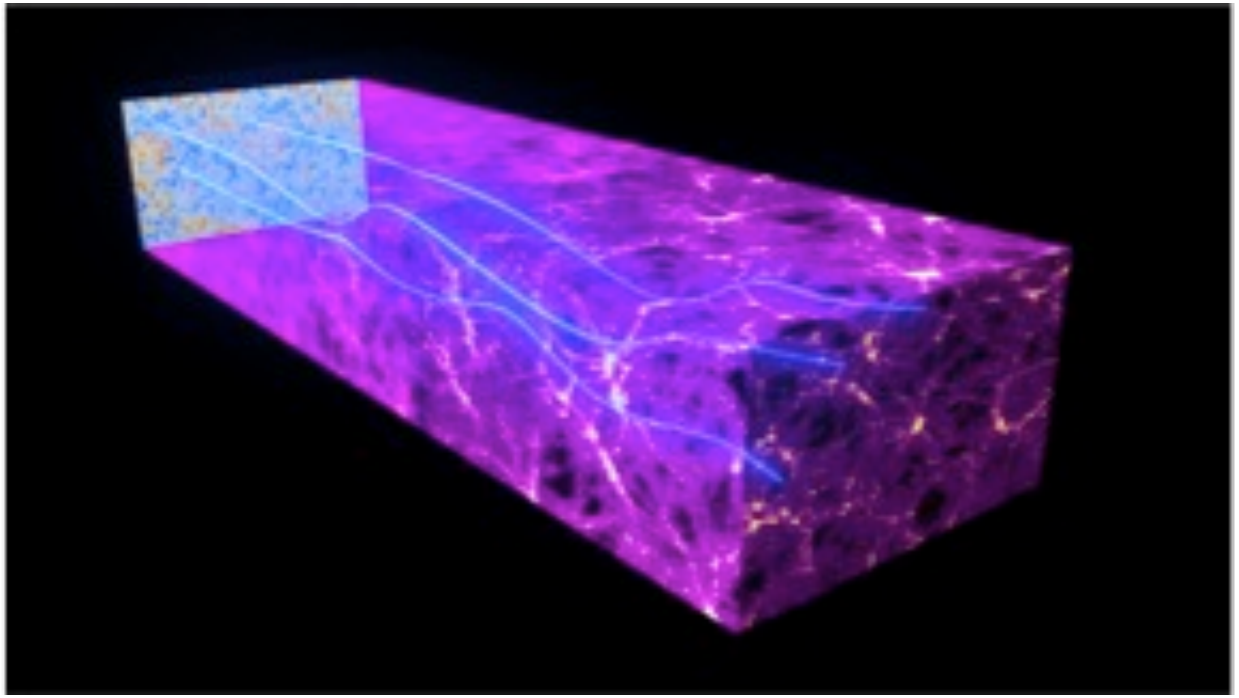
Polarization power spectra



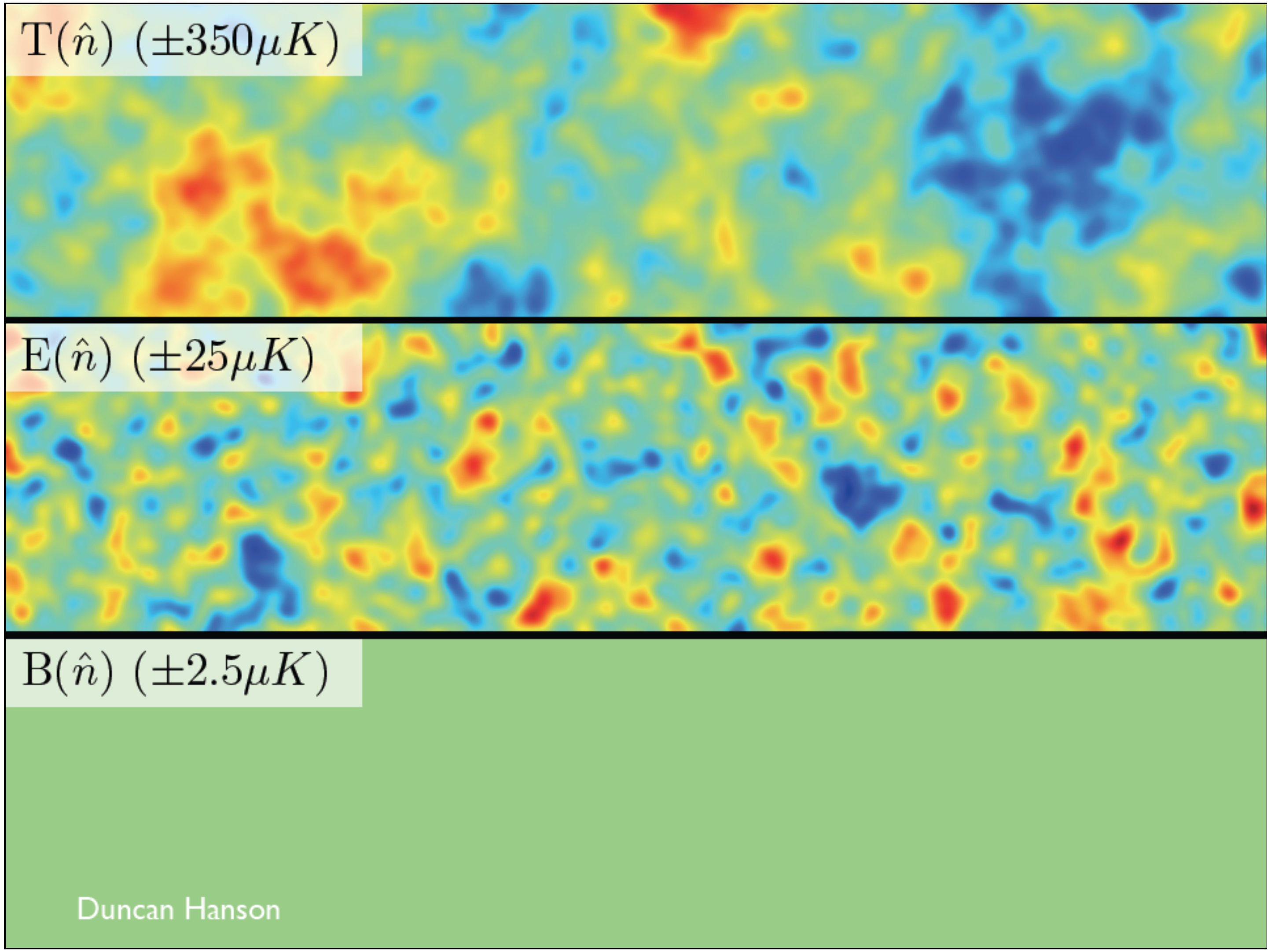
The amplitude of the primordial B-mode is proportional to r, the ratio of the scalar to tensor amplitude

CMB lensing

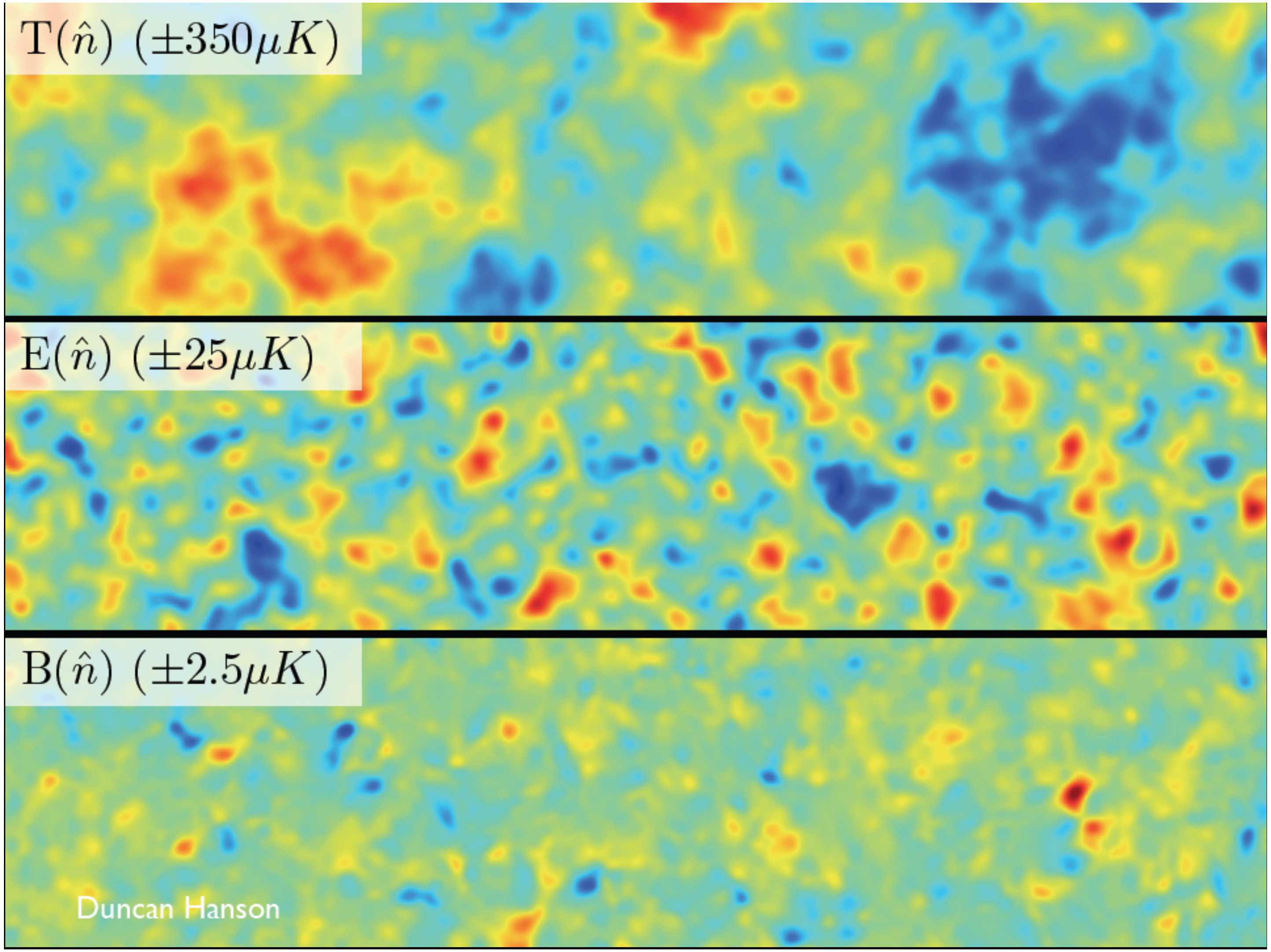
- CMB photons are deflected (typically 2-3 arcminutes) on their way to us by the potentials of the large-scale structure
- It produces a smearing effect of the acoustic peaks of the TT power spectrum and transforms a fraction of E-mode polarization into B-mode at small scales
- It allows to break some degeneracies between cosmological parameters from Planck data alone
- Provides a consistency check between the model inferred at low and high redshift



CMB lensing



CMB lensing



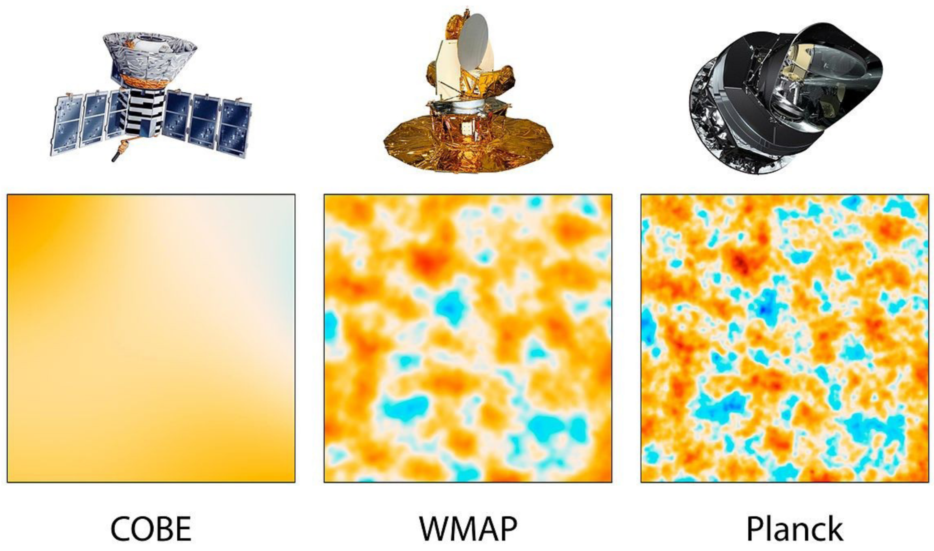
The microwave sky

$$b\,S \quad + b\,F \quad + \quad \boldsymbol{n} = \boldsymbol{d}$$

- The observed microwave sky is a combination of the CMB plus other astrophysical signals (foregrounds) along the line of sight
- The CMB and the foregrounds have a different frequency dependence ⇨ Observe at different frequencies in order to separate the different components
- The main contaminants are diffuse emission from our own Galaxy (synchrotron, free-free, thermal dust) and compact emission from extragalactic sources

The Planck Mission: a story of success

- ESA satellite launched in May 2009 to measure the CMB temperature and polarization over the full sky with high sensitivity at an angular resolution ~5 arcminutes
- Two instruments:
  - LFI : observing at 30, 44 and 70 GHz (PI. N. Mandolesi)
  - HFI: observing at 100, 143, 217, 353, 545 and 857 GHz (PI. J.L. Puget)
- Nominal Mission
  - 2 full sky surveys
- Extended mission
  - 5 sky surveys with HFI
  - 8 sky surveys with LFI
- End of operations: Oct. 2013

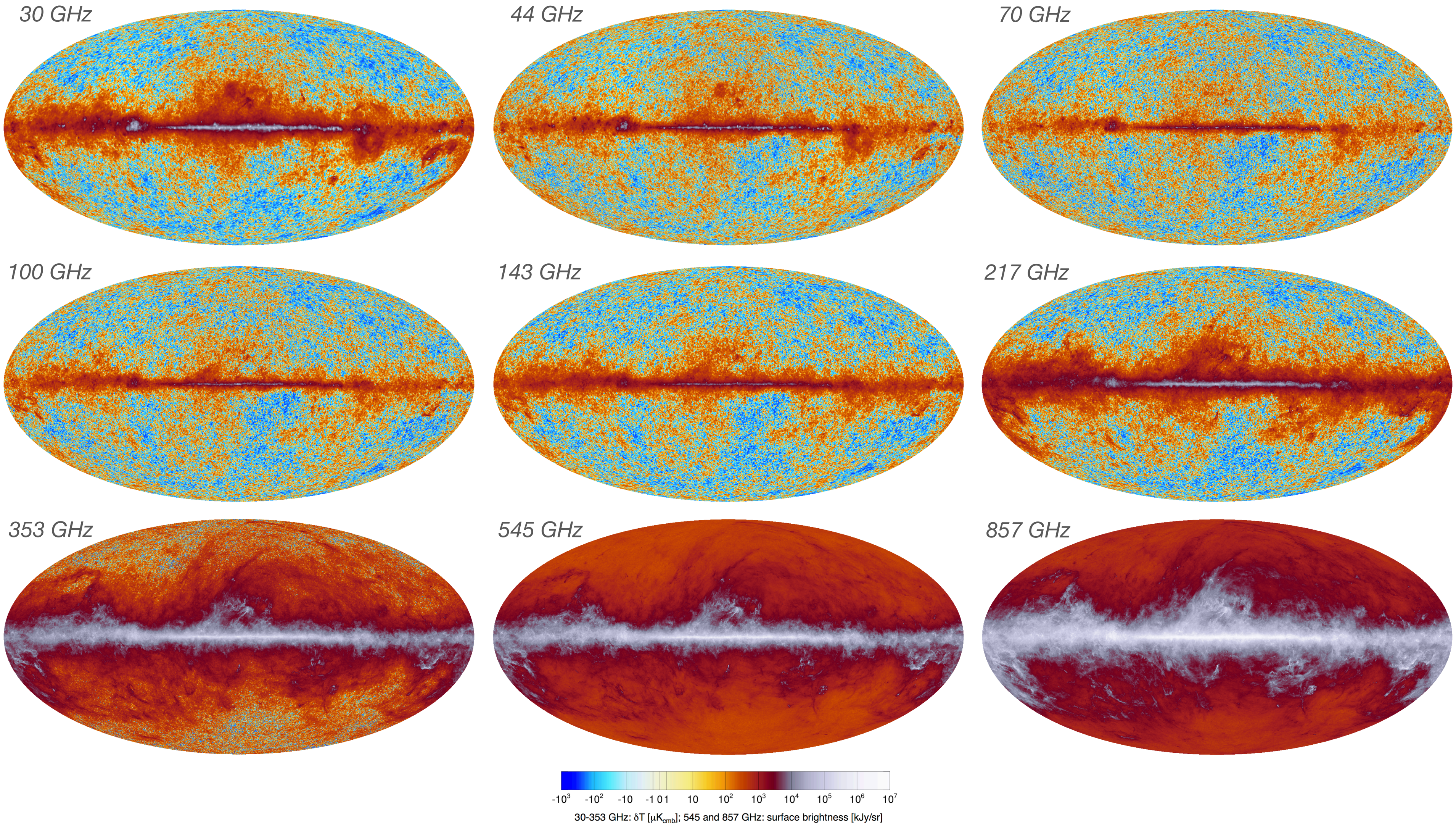


Planck publications and products

2010: Planck pre-launch papers	13 publications describing the technical capabilities of Planck's instruments
2011: Planck Early papers	27 publications coming with the 1st delivered product: The Early Release Compact Source Catalogue
2012 - 2018 : Planck intermediate results	54 publications mainly on galactic and extragalactic astrophysics
2013 : Planck 2013 results	32 publications on cosmology science from CMB temperature data. Maps, C_l's and likelihoods delivered
2015: Planck 2015 results	28 publications mainly on cosmology science from CMB temperature and polarization data (full mission). Update of the delivered products, including polarization.
2018: Planck 2018 results	12 papers. Legacy products and final results

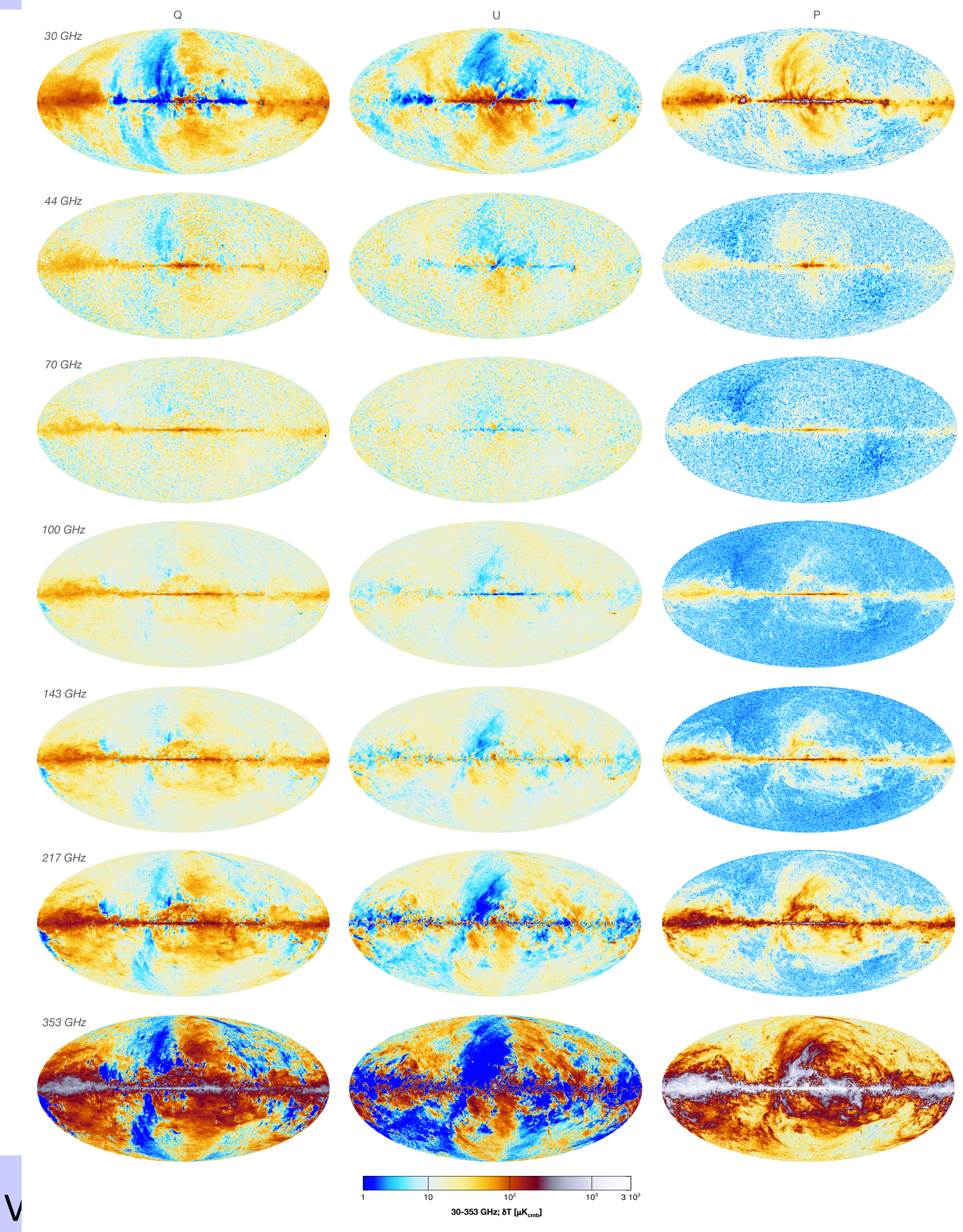
Planck papers and products can be found at the PLA: http://pla.esac.esa.int/pla/

The sky as seen by Planck: intensity



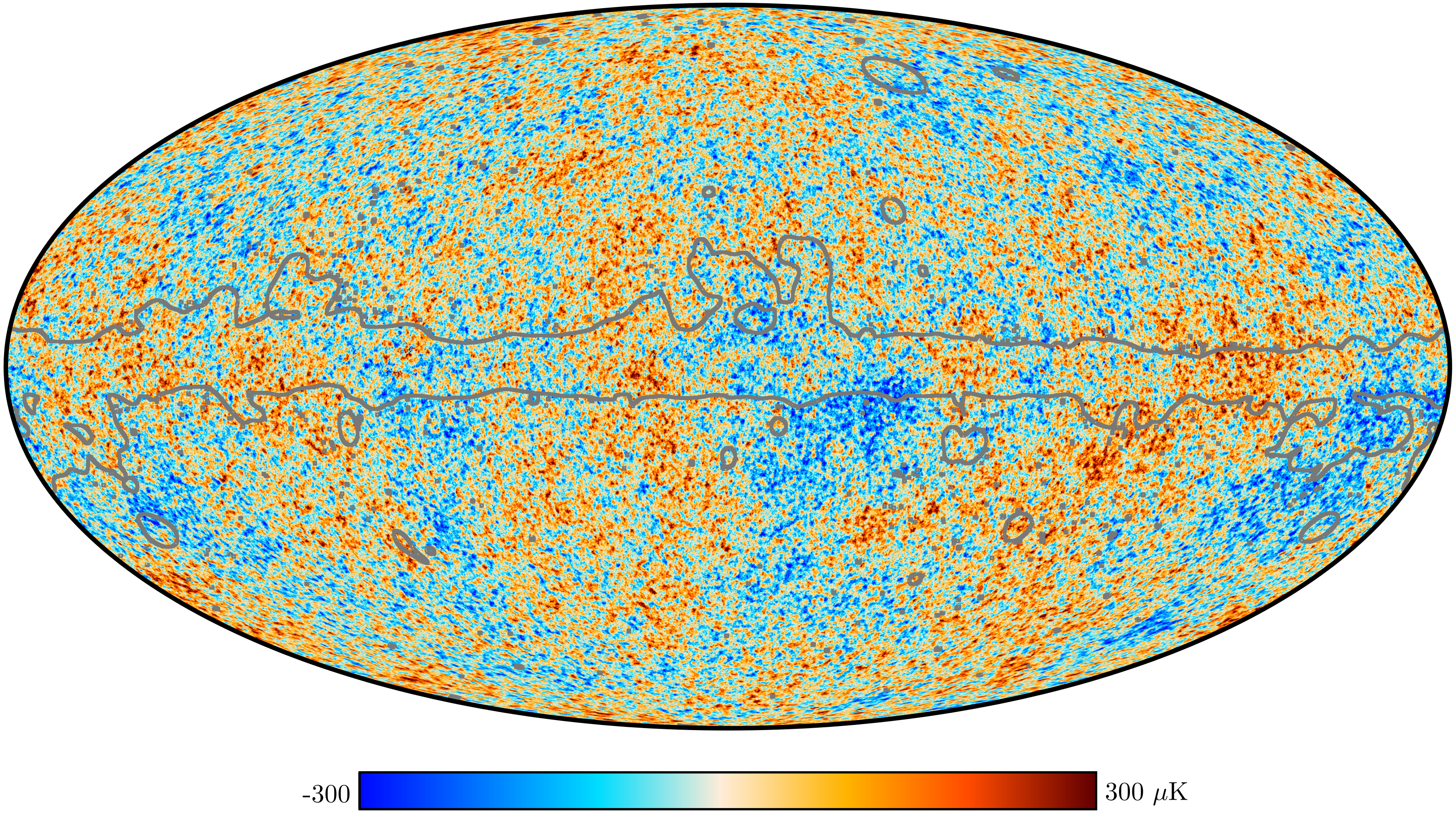
Planck 2018 Results I

The sky as seen by Planck: polarization



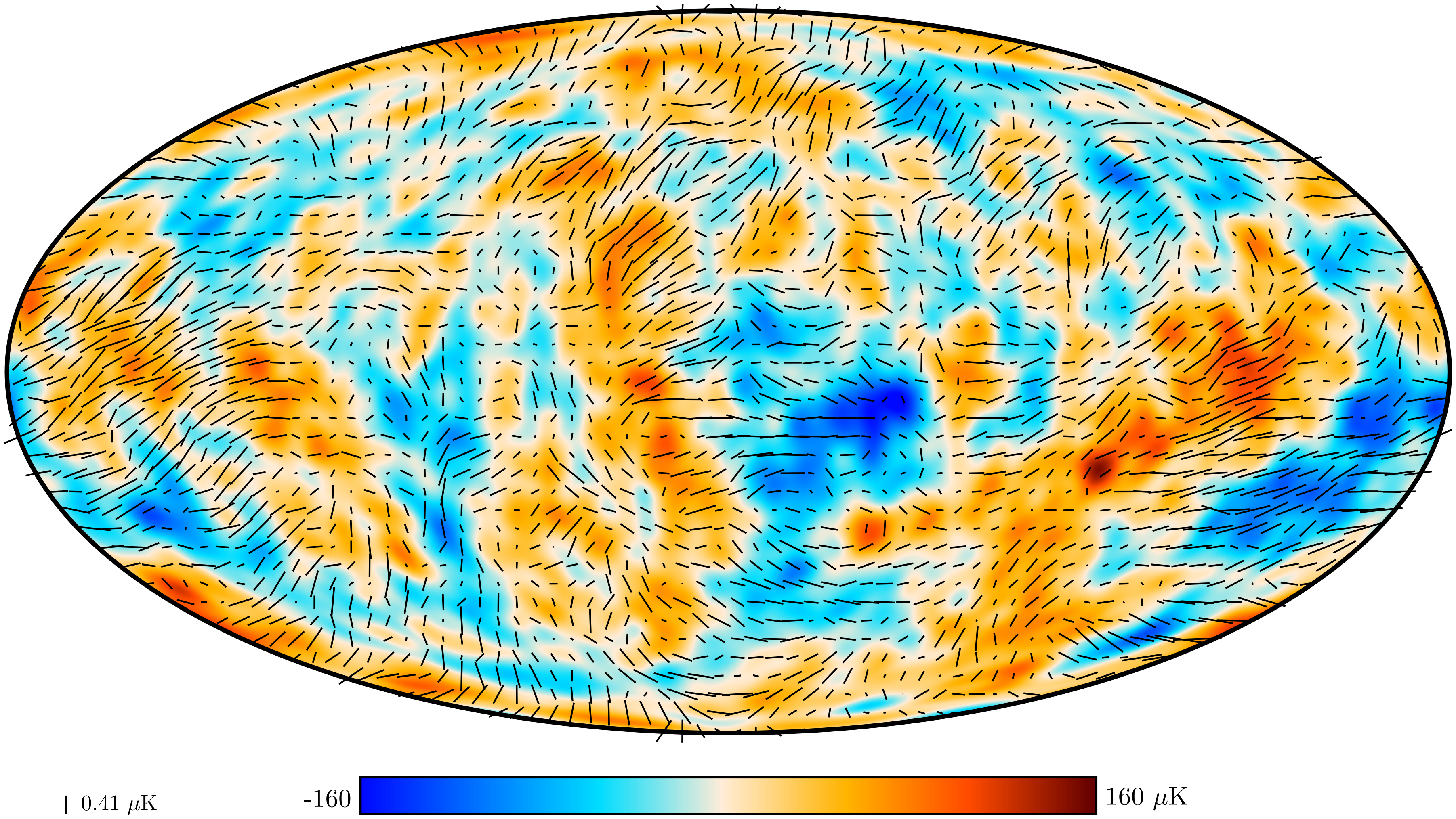
Planck 2018 Results I

Planck CMB temperature (inpainted)



Planck 2018 Results I

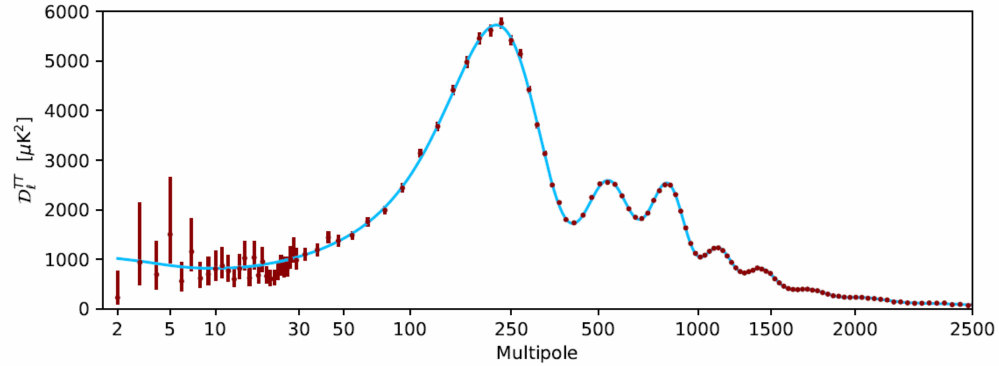
Planck CMB polarization



Planck 2018 Results I

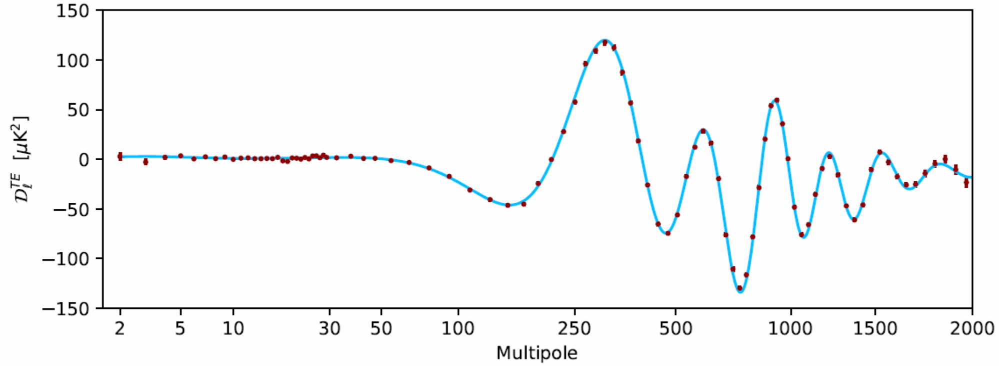
Power spectra

TT spectrum



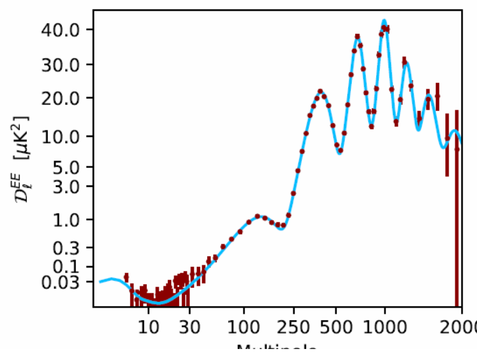
CV limited up to ℓ ~1800

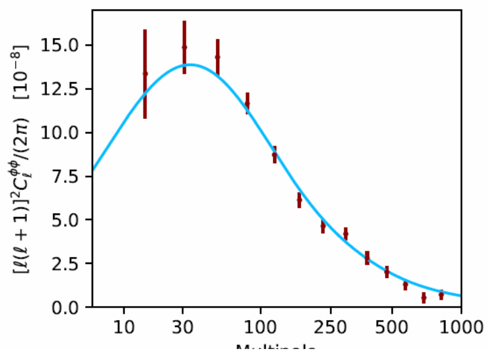
TE spectrum



18 acoustic peaks mapped in TT, TE and EE

EE spectrum





$\phi\phi$ spectrum

Excellent agreement with the spatially-flat six-parameter ΛCDM model!

Planck 2018 Results I

Baseline ΛCDM results from Planck

Temperature + Polarization + CMB Lensing

	Mean	σ	[%]
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.7
$\Omega_c h^2$ DM density	0.1200	0.0012	1
100θ Acoustic scale	1.04092	0.00031	0.03
τ Reionization optical depth	0.0544	0.0073	13
$\ln(10^{10}A_s)$ Power spectrum amplitude	3.044	0.014	0.7
n_s Scalar spectral index	0.9649	0.0042	0.4
H_0 Hubble parameter	67.36	0.54	0.8
Ω_m matter density	0.3153	0.0073	2.3
σ_8 matter perturbation amplitude	0.8111	0.0060	0.7
z_{re}	7.68	0.79	10.2

Many parameters determined at sub-percent level !

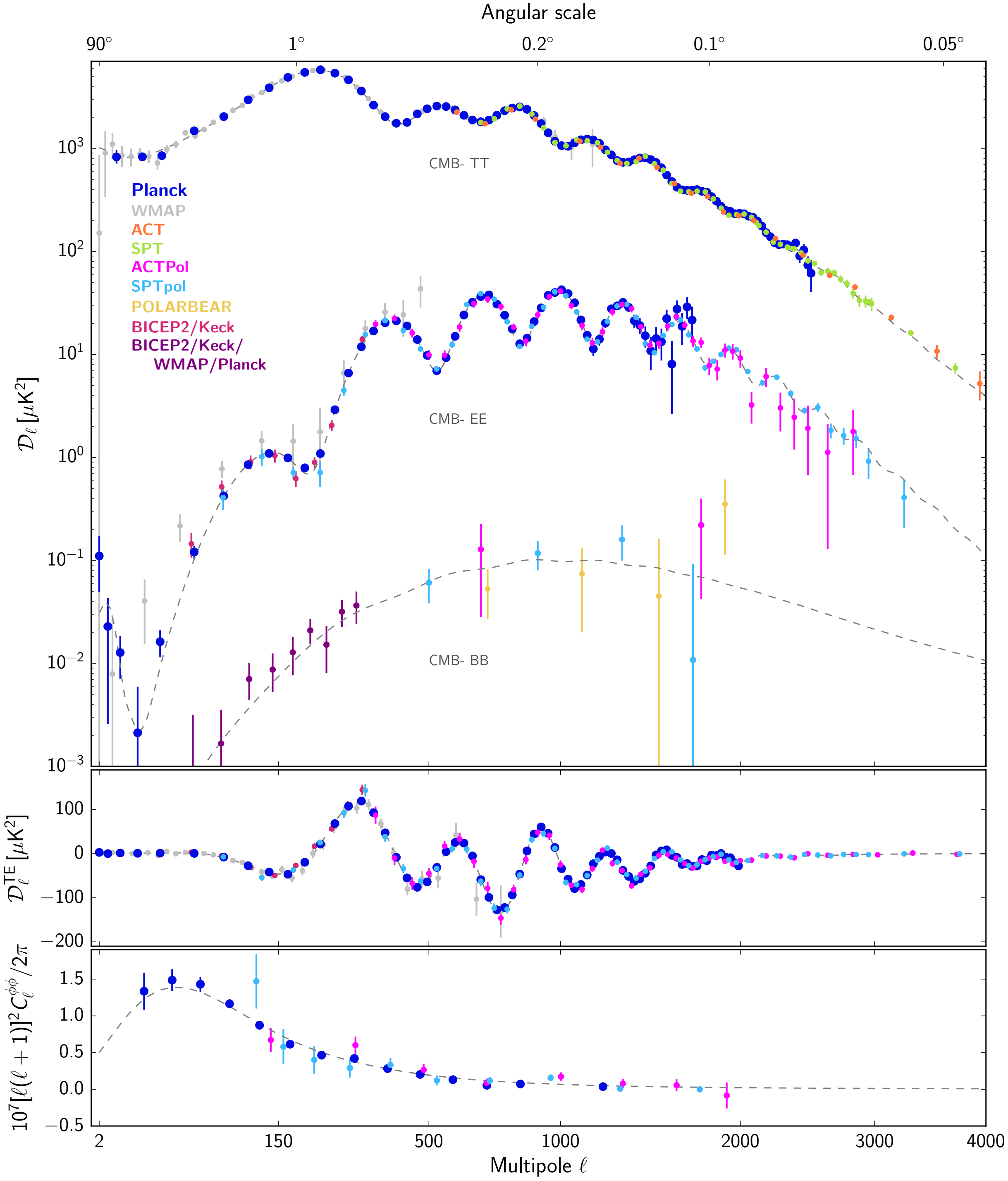
τ lower and tighter determination due to use of HFI pol. data at large scales (τ=0.067±0.022 in 2015)

n_s is 8σ away from scale invariance

Best (indirect) determination of the Hubble constant up to date

Robust against changes of likelihood at < 0.5σ

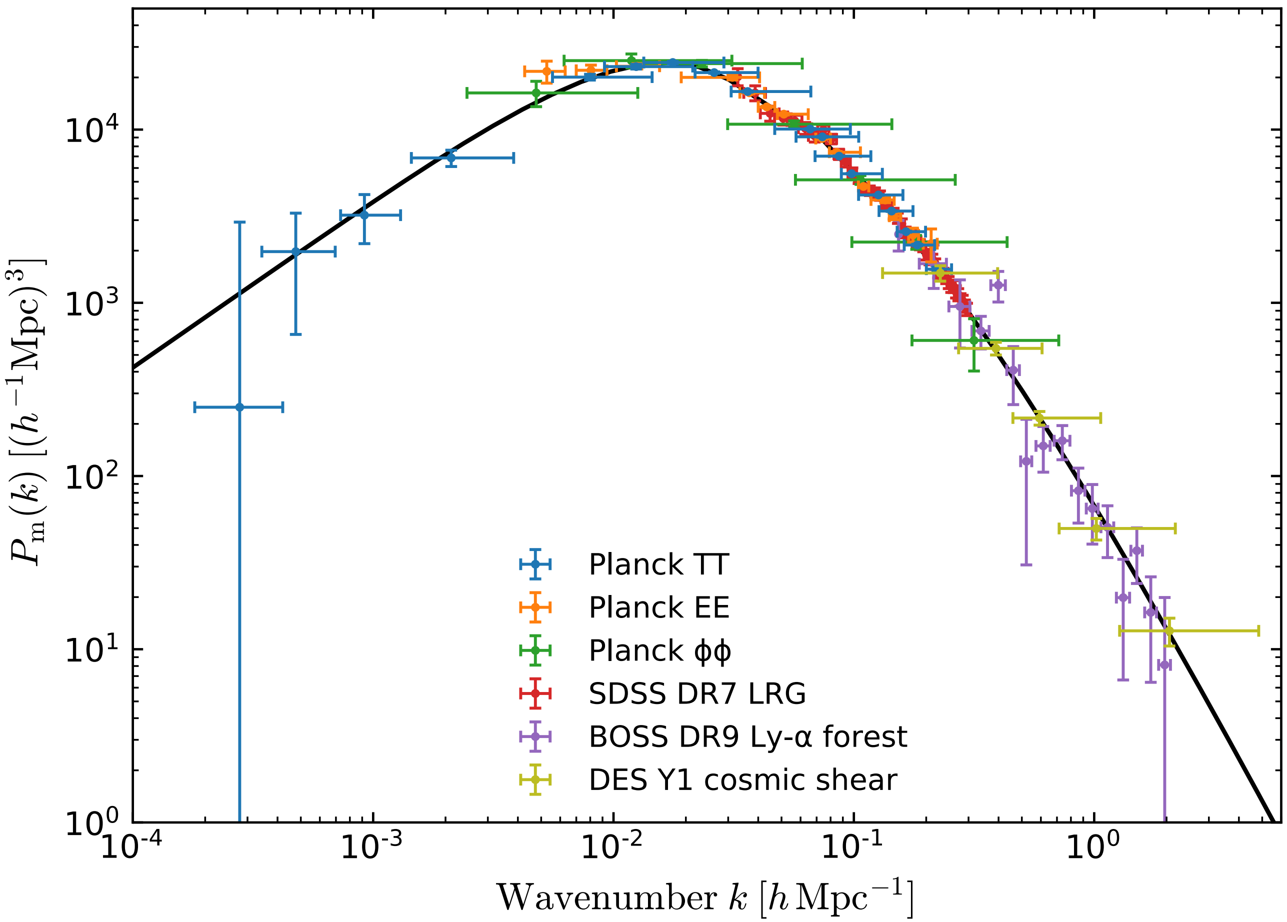
Planck 2018 Results VI



Good agreement with other other CMB data sets

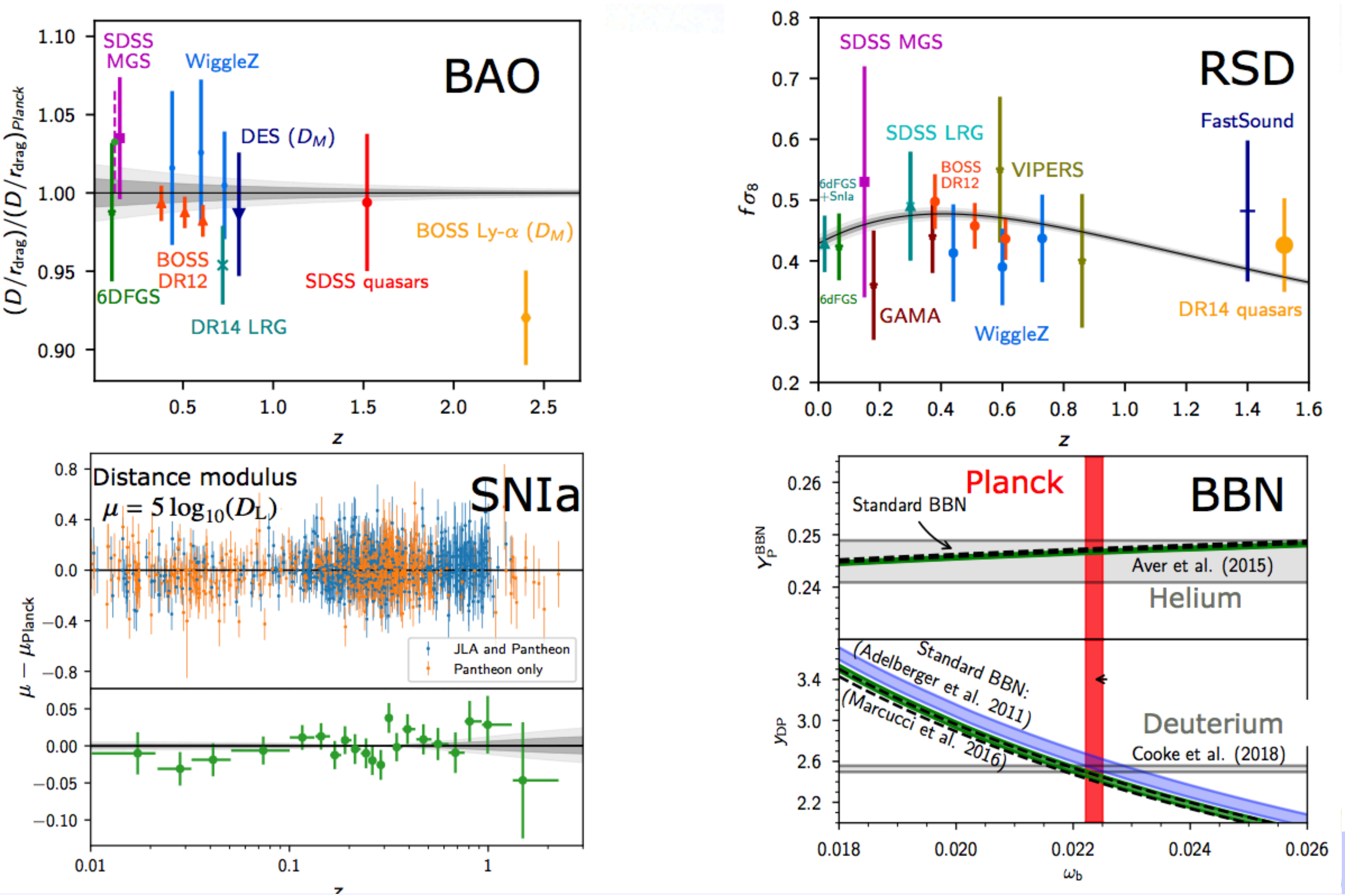
Dashed line corresponds to the Planck best fit ΛCDM model

The linear matter power spectrum (at z=0)



Cosmic concordance: data spanning 14 Gyr in time and 3 decades in scale

Good consistency with other cosmological probes



But…

- There is a strong tension with direct measurements of the expansion rate of the universe H_0 using SNIa.

  H_0=67.36±0.54 km/s/Mpc Planck ΛCDM

  H_0=73.5±1.6 km/s/Mpc PSH0ES (Riess et al. 18)

  3.6σ tension

- Other measurements of H_0:

  Inverse distance ladder:

  H_0=67.9±1.3 km/s/Mpc galBAO+(BBN+deuterium)+CMB lensing (or LyαBAO or DES lensing)

  Time delay muliple-imaged quasars

  $H_0=72.5^{+2.1}_{-2.3}$ km/s/Mpc H0LiCOW (Birrer et al. 2018)

Talks by P. Lemos, E. di Valentino

- None of the studied extended models convincingly solves the tension
- Unaccounted systematics? New physics?
- Other mild tensions (e.g. BOSS-Lyα, joint DES yrs1 results, extra lensing preferred by TT) but at a lower level

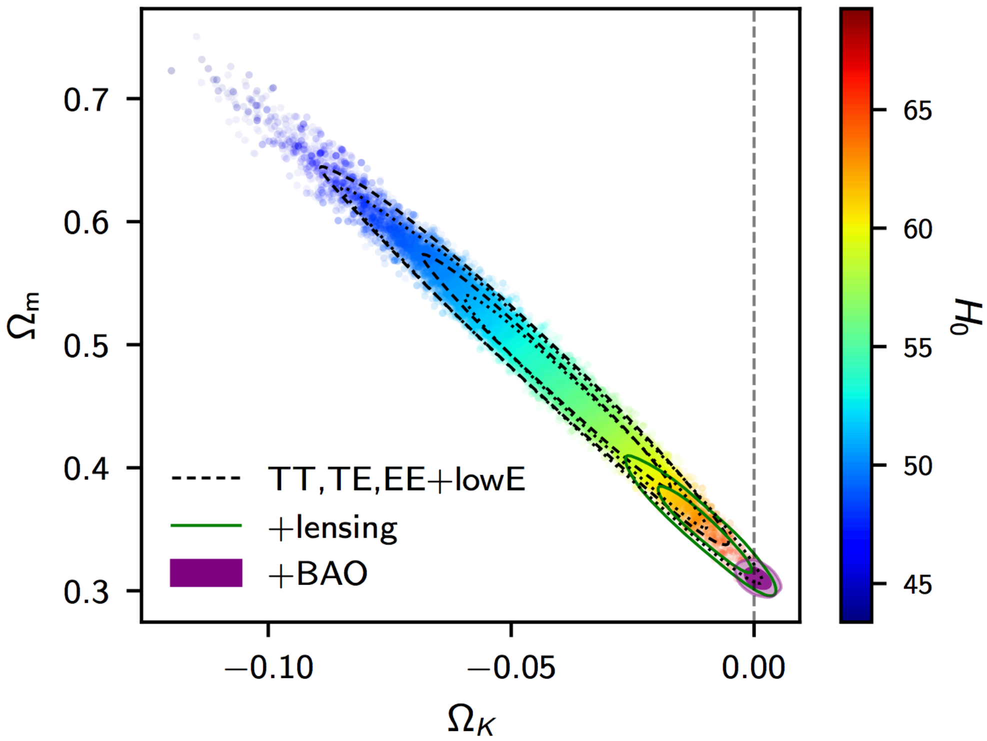
Inflation scorecard

Prediction	Measurement
A spatially flat Universe,	Ω_k=0.0007 ± 0.0019
with a nearly scale-invariant (red) spectrum of density perturbations,	n_s = 0.967 ± 0.004
which is almost a power law,	dn/dlnk = -0.0042 ± 0.0067
dominated by scalar perturbations,	$r_{0.002}$ < 0.056 (95% CL)
which are Gaussian	f_{NL} = 2.5 ± 5.7
and adiabatic,	α_{-1} = 0.00013 ± 0.00037
with negligible topological defects	f < 0.01

And a background of primordial gravitational waves… not detected yet

Planck 2018 Results. I

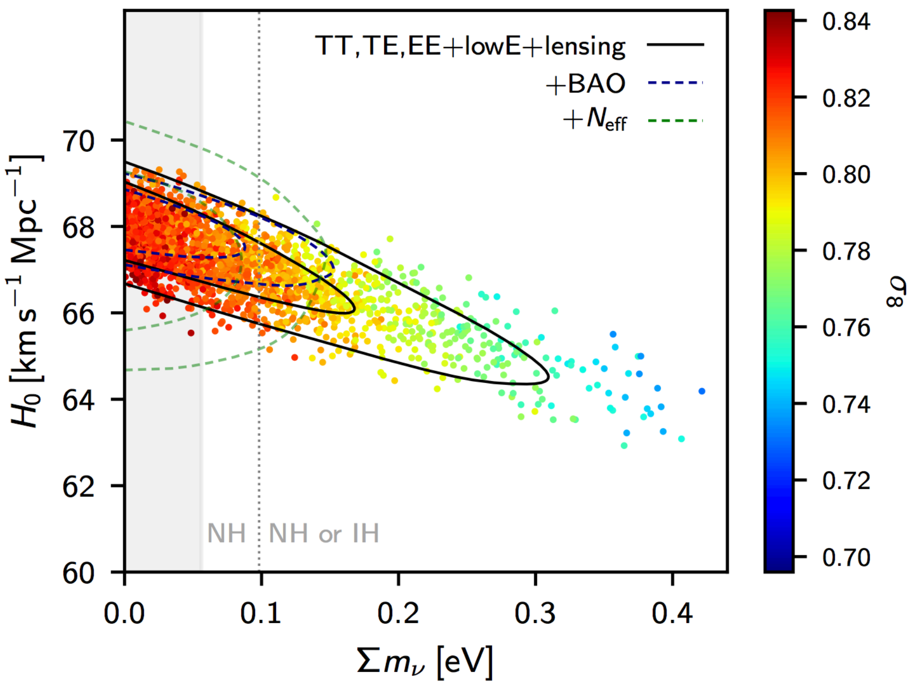
ΛCDM Extensions: curvature



- Ω_k<1 can provide larger lensing amplitude, thus preferred by CMB spectra
- When adding CMB lensing reconstruction, less preference for deviations, further tightened by BAO.

$$\Omega_K = 0.0007 \pm 0.0019 \quad (68\,\%,\ \mathrm{TT,TE,EE{+}lowE{+}lensing{+}BAO}).$$

ΛCDM Extensions: neutrinos masses



- Non-relativistic at late times.
  At large scales: changes early and late ISW.
  At small scales: larger Σm_ν suppresses lensing. High lensing preference of high-l forces constraint on Σm_ν to be tighter.
- Constraint from 2015 improved by about 30% (TT)-50%(TTTEEE) due to lower and tighter τ and change in polarization systematics.
- TTTEEE constraint differ in CAMspec by **15%**. Reduced when adding BAO.

$\sum m_\nu < 0.26$ eV (95 %, *Planck* TT,TE,EE+lowE). [<0.492 (2015 TTTEEE+lowP)]

$\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

Close to disantangle inverted/ normal hierarchy

Material from S. Galli

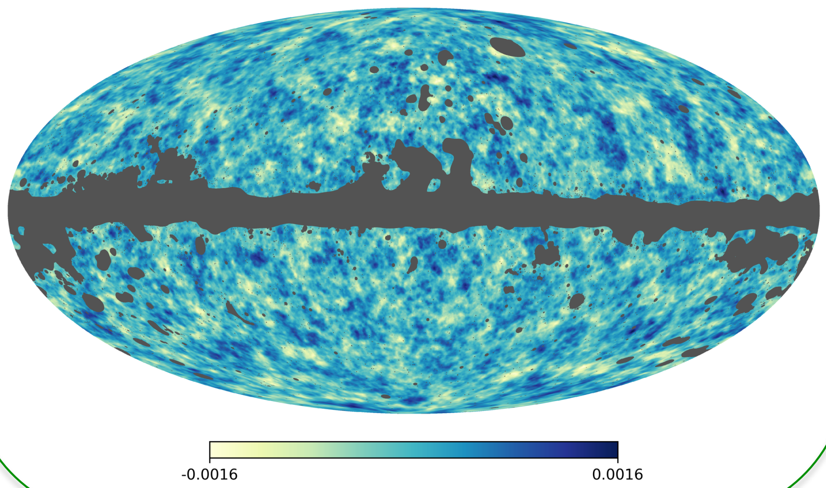
Isotropy and statistics

- Planck has shown that the CMB fluctuations (in T and P) are, overall, in good agreement with the Gaussian properties and Isotropy expected from the standard cosmological model
- Large scale anomalies (at ~2-3σ) in T have been confirmed with Planck data (deficit of power in large scales, hemispherical power asymmetry, point-parity asymmetry, a large cold spot in the southern hemisphere...)
- Analyses of polarization data have not shown convincing detection of anomalies related to T. However, the Planck sensitivity in P is too low to shed light on the origin of these features → a new CMB polarization satellite is required
- Interestingly, there is a hint of power asymmetry in polarization with the same orientation as that in temperature, although not at a convincing significance
- If the anomalies are just statistical flukes or indicative of new physics remain to be solved

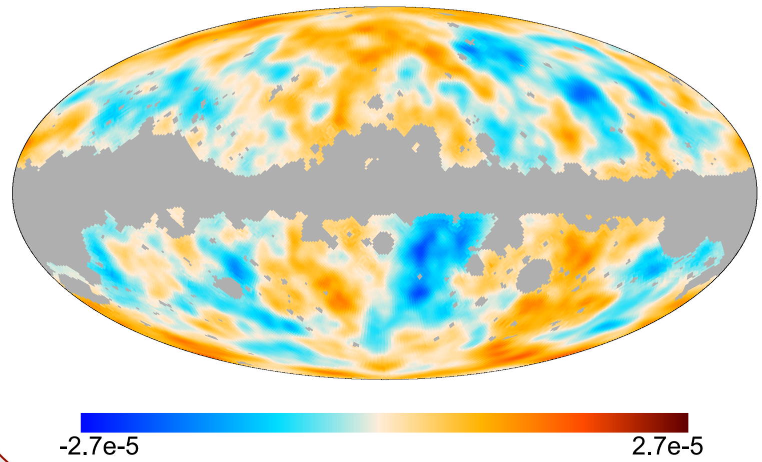
Secondary anisotropies

Besides the directly related CMB science, *Planck* has provided us **with a lot of additional science**:

The already mentioned **lensing potential**, which has been very important to constrain ΛCDM (40σ detection)

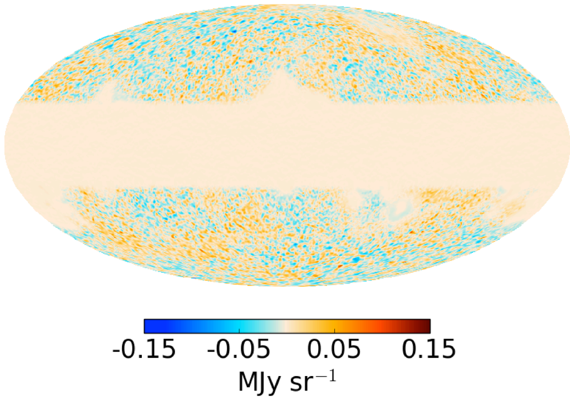


The **ISW fluctuations**, detected (at $\approx 3\sigma$) completely with Planck only data (CMB and lensing), providing complementary evidence of the accelerated expansion of the universe (with external tracers $\approx 4\sigma$ significance)



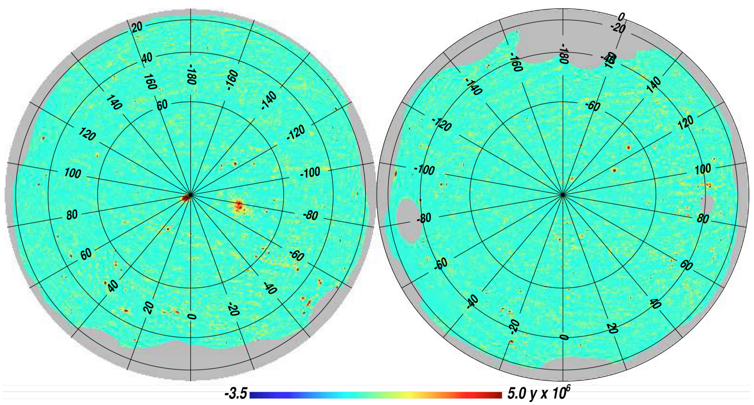
Maps of CIB and thermal SZ

A map of the **CIB**, allowing, also, for a better determination of the thermal dust, and offering a new window for future *delensing* of CMB experiments looking for primordial tensor perturbations.



CIB at 857GHz, 1 degree

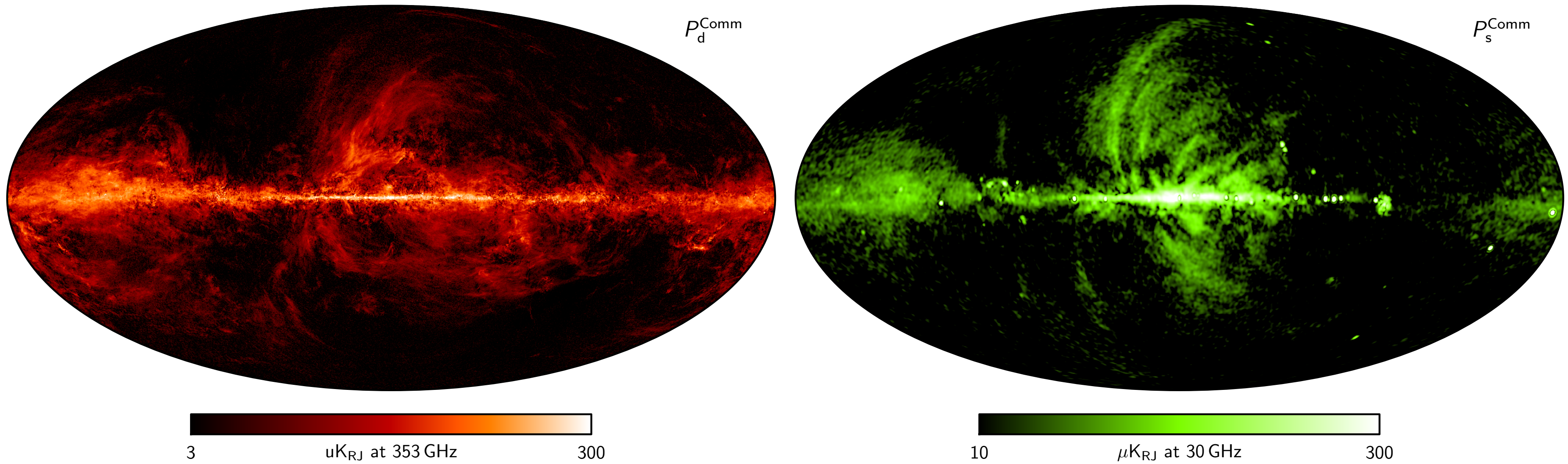
A map of **diffuse thermal SZ,** which is an complementary cosmological probe



SZ, Compton parameter

Galactic emissions

A lot of detailed information on the spatial variation of Galactic emissions (e.g., synchrotron, dust), both, in temperature and polarization, as well as of the galactic magnetic field. This is crucial information for future CMB polarization experiments.

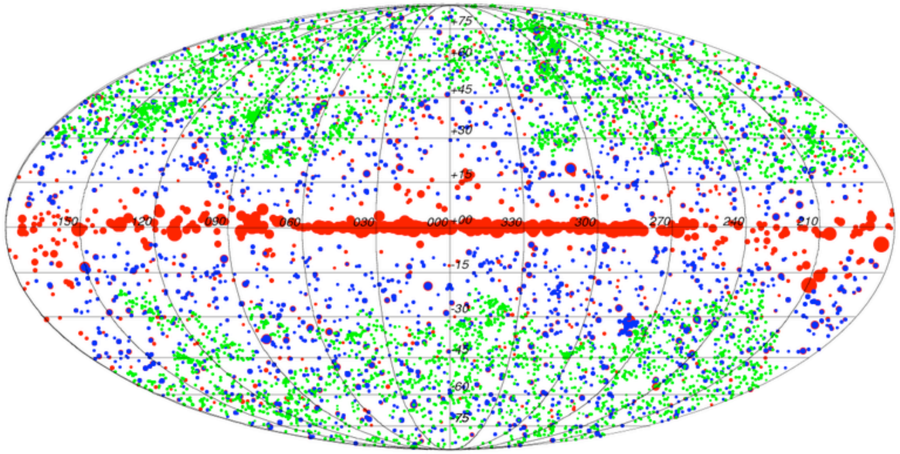


Thermal dust and synchrotron amplitudes in polarization

Planck 2018 Results. IV

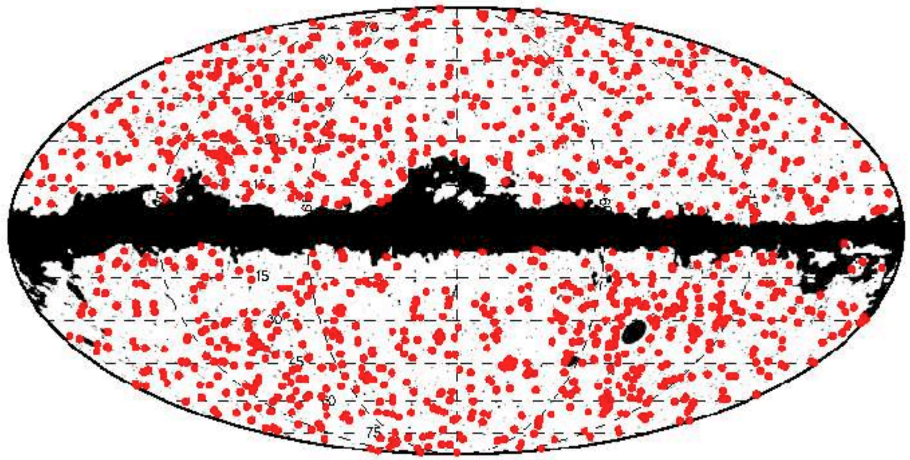
Catalogues

Catalogues of extragalactic sources (radio and infrared: a few 10000s) and clusters of galaxies (via thermal SZ: >1000)



Extragalactic sources (30, 143 and 857GHz)

Planck SZ catalog



Cluster catalogue via tSZ

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

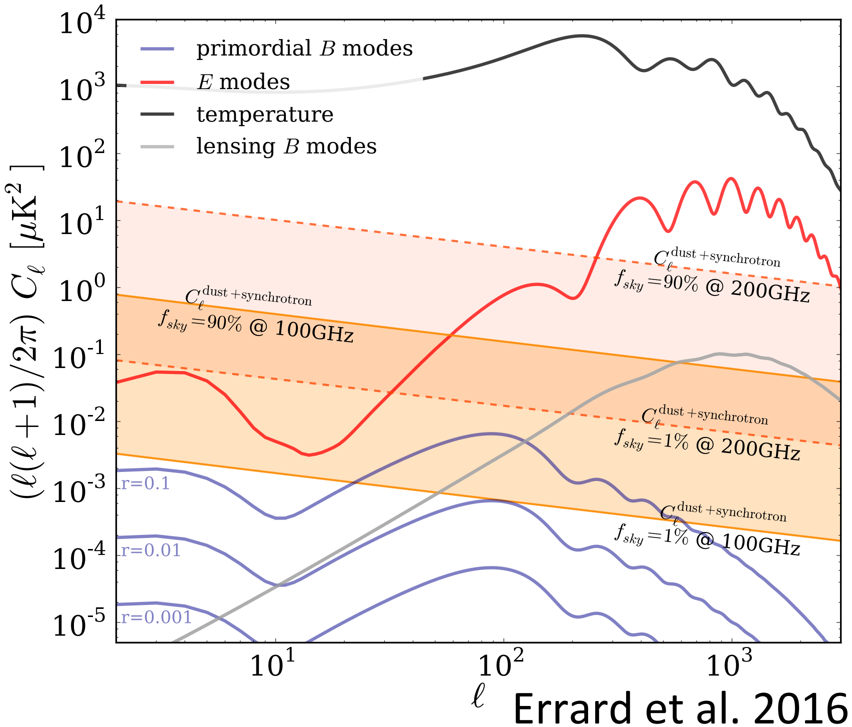
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

The roadmap towards the B-mode detection

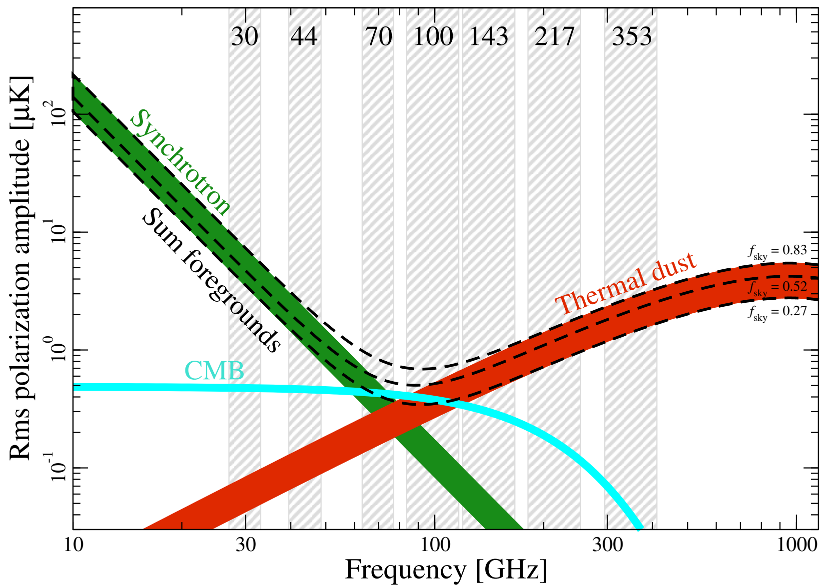
The detection of the B-mode is extremely challenging, it requires:

- **High-sensitivity experiments** (very weak signal)
- **High resolution** (if *r* too low ➔ perform delensing)
- **Low systematics** (many systematics can produce E➔B leakage)
- **Large frequency coverage** (to remove foregrounds: synchrotron at low frequencies and thermal dust at high frequencies are the main contaminants)

Two complementary approaches: ground-bases versus space missions



Errard et al. 2016



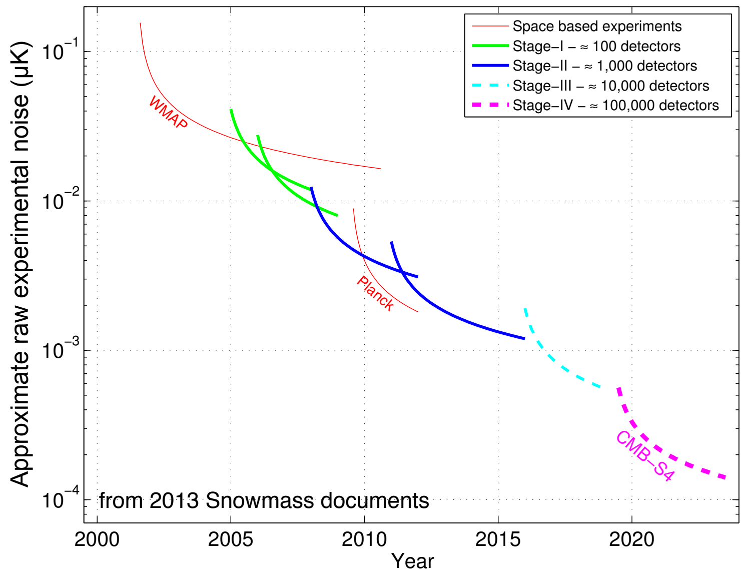
40 arcmin resolution

Planck 2018 Results. IV

Ground-based experiments

- CMB Stage-4: led by US with small contributions from Europe
  Two main sites: Atacama (Chile), South Pole

"Moore's Law" of CMB sensitivity



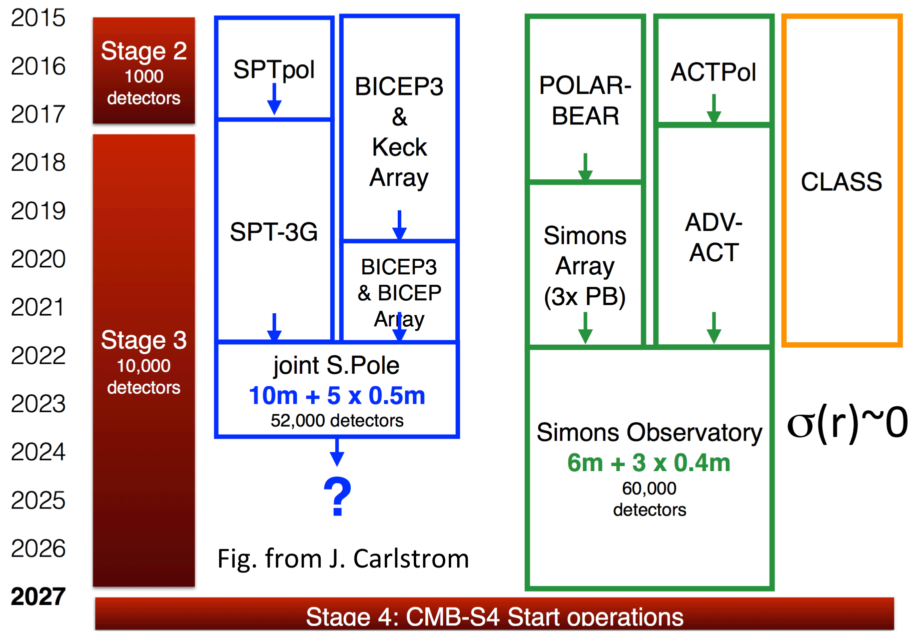


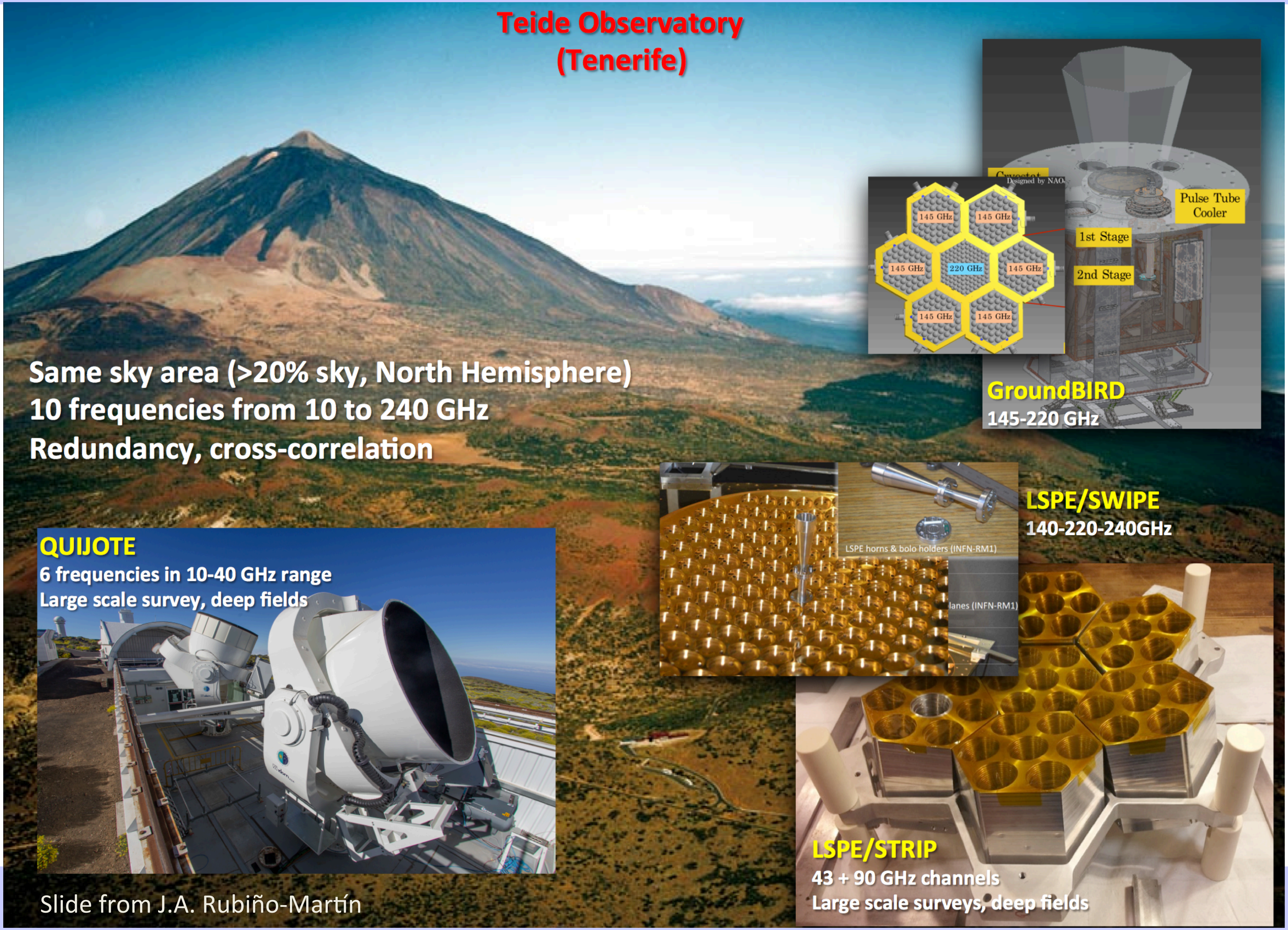
Fig. from J. Carlstrom

$\sigma(r)$~0.003

$\sigma(r)$~0.0005

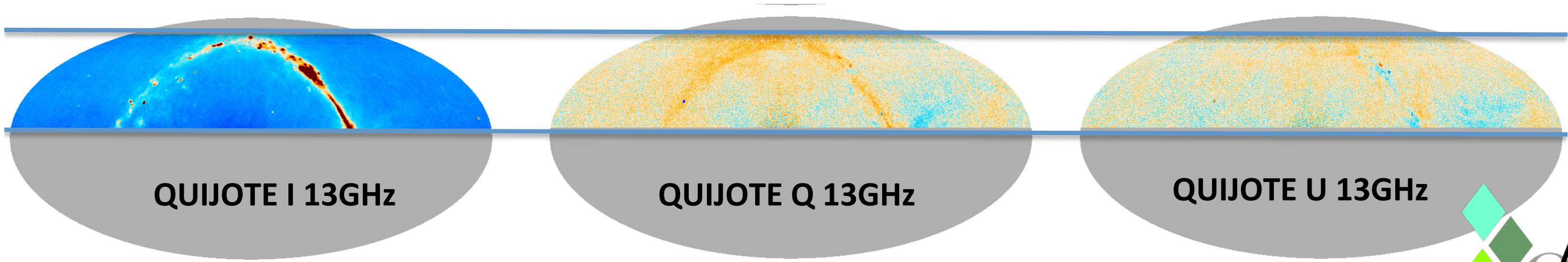
- QUBIC: Q & U bolometric interferometer for cosmology (led by Europe)
  - First bolometric interferometer
  - Alto Chorrillos site, Argentina; first tests in 2019
  - First module aiming at $\sigma(r)=0.01$

Ground-based experiments: Tenerife site



The QUIJOTE Experiment

- **Site**: Teide Observatory (altitude 2400 m, 28.3º N, 16.5 W)
- **Frequencies**: 11, 13, 17, 19, 30 and 40 GHz.
- **Angular resolution**: 0.92º to 0.26º
- **Sky coverage**: -32º < Dec. < 88º (f_{sky}=0.65).
- **Observing strategy**: Deep observations in selected areas plus wide survey



Preliminary maps from QUIJOTE at 13 GHz, wide survey

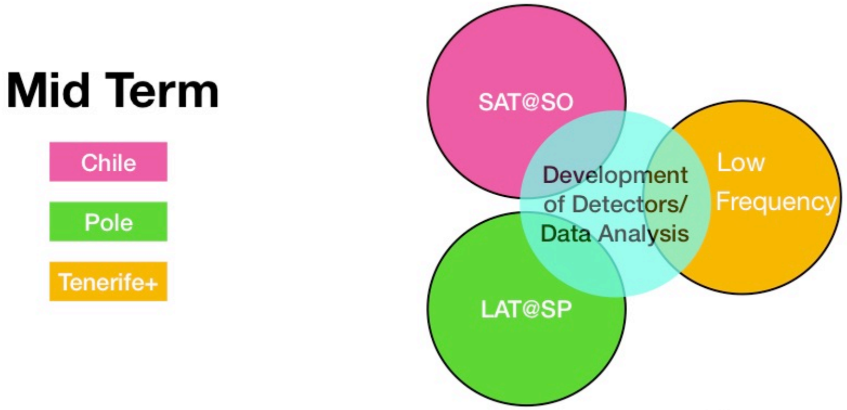
→ See talk by Federica Guidi on Wednesday

Quijote
Q-U-I Joint Tenerife CMB experiment

European coordination

Three different European initiatives:

- SAT at Simons Observatory (UK)
- LAT at South Pole (Germany)
- Low Frequency 10-120 GHz (Spain, Italy, UK)→ ELFS



Convergence process by 2027:

- High frequency
- Low frequency

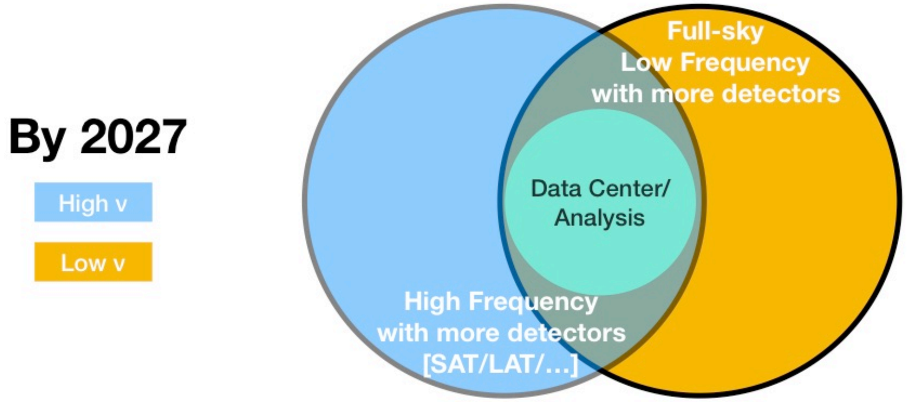


Fig. from E. Komatsu

ELFS: European Low Frequency Survey

- Full-sky, ground-based
  - Two sites: Tenerife, Atacama?
  - Two 6-meter class telescopes
- Low frequencies: synchrotron dominated range
  - 10-40 GHz (radiometers): essential complement to CMB-S4 and satellites
  - 75-120 GHz (KIDs arrays): no other high-frequency, high-resolution experiment in the north
- Resolution ≈20 arcmin

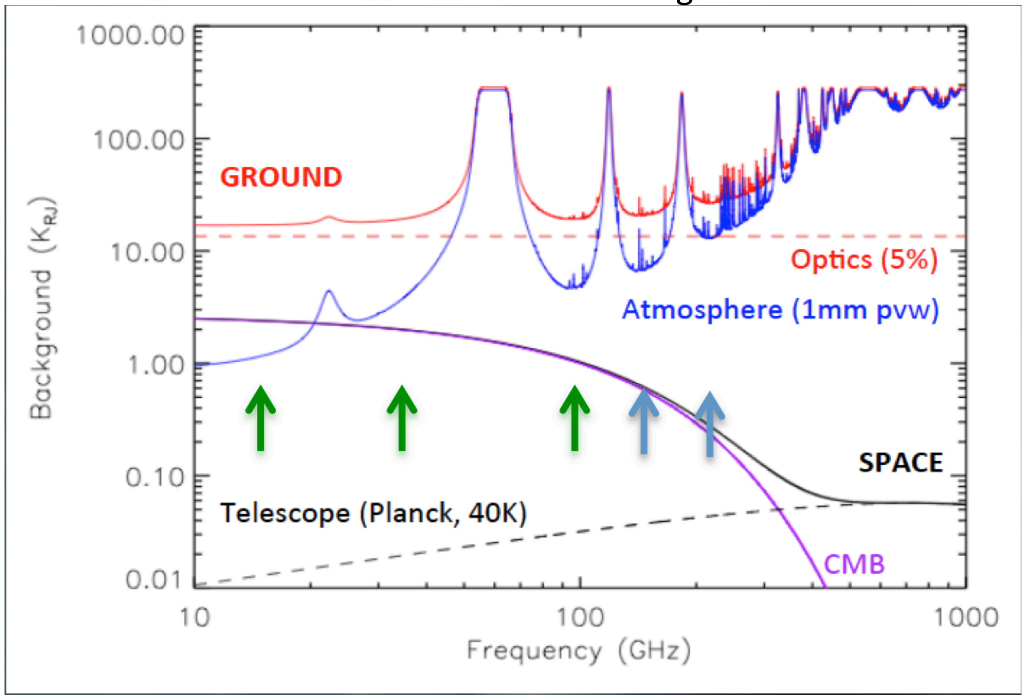
Preliminary studies indicate that is possible to detect $r \approx 10^{-3}$ with this strategy → talk by E. de la Hoz

Space missions

Fig. from M. Hazumi

Why to observe from space?
It provides an ideal environment:

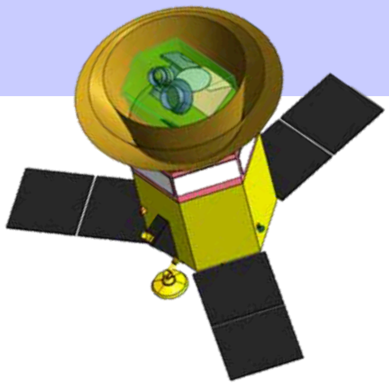
- No uncertainties from atmosphere
- No limitation in the choice of observing bands (except CO)
- No ground pick-up
- Only way to access lowest multipoles



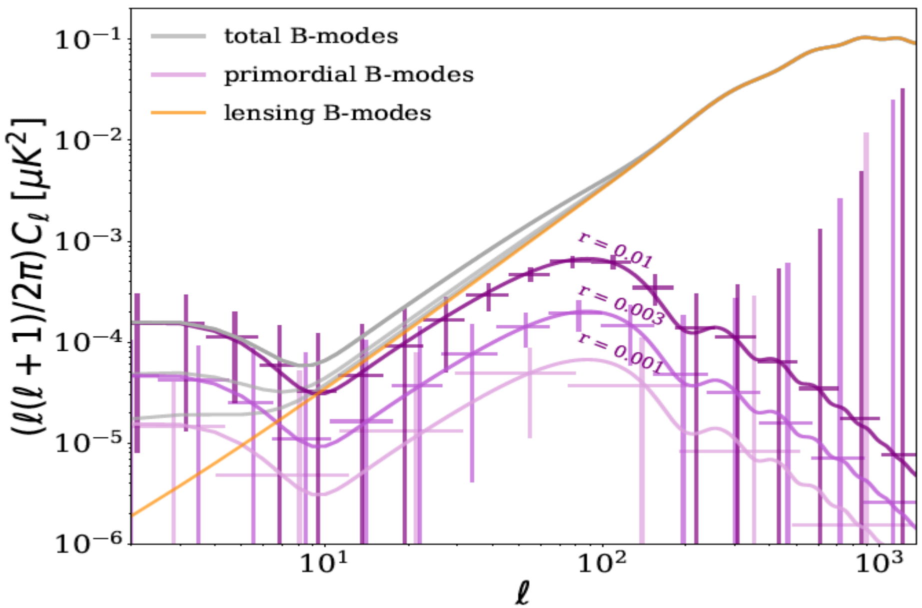
Rule of thumb: 100 detectors in space ~100.000 detectors on ground

Different proposals for the next CMB satellite: CORE (ESA, not selected), PICO (NASA funded study), LiteBIRD (JAXA), CMB-Bharat (ISRO)

LiteBIRD



- ***LiteBIRD*** is a JAXA proposal (PI: Masashi Hazumi) for an L-class mission, with contributions from US, Canada and Europe (including Spain)
- On 21st May, JAXA selected *LiteBIRD* ➔ launch expected in 2027.
- It will observe in L2 for 3 years.
- 15 bands (34-448 GHz)
- Sensitivity < 3 μK arcmin



Full Success :
$\sigma(r) < 1 \times 10^{-3}$ (for r=0)
$2 \leq \ell \leq 200$

Extra Success :
Improve $\sigma(r)$ with external data: delensing and additional foreground cleaning (from low frequencies)

LiteBIRD will also provide **E-mode maps** limited by **cosmic variance at scales < 1 degree**.

Conclusions

- Planck has shown that the base-ΛCDM model fits all CMB data (temperature, polarization, lensing) plus many other cosmological probes. Many cosmological parameters determined at per cent level.
- Density fluctuations consistent with predictions from inflation. No primordial gravitational waves detected yet.
- However, a strong tension (3.6σ) with direct measurements of H_0 remains.
- Origin of CMB anomalies not clear yet.
- Next challenge: improve polarization measurements and the quest of the intrinsic B-mode of polarization.
- Also much to learn from secondary anisotropies (lensing, SZ) and foregrounds.
- Exciting results to come in the next years…